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FRACTURE MECHANICS APPLICABILITY TO PORTLAND CEMENT CONCRETES

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Champaign, Illinois

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by

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FOREWORD

This paper was presented at the Army Science Conference held at U.S. Military Academy, West Point, NY, 21 June 1972.

This investigation was conducted by Materials Division of the Construction Engineering Research Laboratory (CERL) in Champaign, Illinois. The work was performed as part of an In-House Laboratory Independent Research project. Technical Monitor was Colonel E. S. Townsley.

CERL personnel directly concerned with this study were Dr. D. J. Naus, Dr. J. L. Lott, and Messrs. R. T. Neu, H. R. Brown and J. Gambill. The Director of CERL is Colonel R. W. Reisacher and the Chief of Materials Division is Mr. E. A. Lotz.

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13. ABSTRACT

In this investigation, the applicability of linear-elastic fracture mechanics to portland cement pastes, mortars, and concretes was determined by the fabrication, testing, and analysis of plate specimens containing a precast flaw. The results indicate that: the concepts of linear-elastic fracture mechanics were not directly applicable to concrete materials for the specimen geometry chosen and thus the applicability of fracture mechanics to concrete materials for other specimen geometries and loadings seems questionable; other analytical techniques such as net section stress do not appear applicable as a failure criterion; and, specimens to which strain gages were attached indicate that large localized strains occur in mortars and concretes. A model was developed which provides a qualitative measure of the size of the microcracking zone which occurs in concrete. Experimental results are correlated with the model.

14. KEY WORDS

concrete fracture mechanics microcracking

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INTRODUCTION

Concrete, being a polyphase material, has a more complex fracture process than an ideally brittle material, since fracture can occur by fracture of the cement paste, fracture of the aggregate, failure of the bond between cement paste and aggregate, or any combination of these mechanisms. In addition, during their life, the concrete in structures can be subjected to random loadings and environments which produce complex, varying stress fields which are difficult to analyze using conventional methods. As a result, there have been previously available no common procedures to describe crack propagation in concrete structures. However, a possible solution for understanding the fracture mechanism of concrete does presently exist in the form of fracture mechanics.

Fracture mechanics is the study of the stress and displacement fields in the region of a crack tip in an ideal, homogeneous, elastic material at the onset of rapid, unstable crack propagation; i.e., fracture. The objective of fracture mechanics is to duplicate and measure in a laboratory specimen the conditions of fracture in a service structure. It is based on the premise that if the elastic stresses and strains which completely surround the small inelastic zones in the region of a crack tip are the same in two members, then the stresses, strains, and the fracture mechanisms in the inelastic zones will be the same even if they are indeterminate. A one parameter description of the measure of the stresses and strains in the region of the crack tip is contained in the stress intensity factor which at the onset of rapid, unstable crack propagation becomes a constant for a particular material and is called the fracture toughness (material's resistance to propagation of an existing flaw).

SCOPE

The applicability of linear-elastic fracture mechanics to cement paste, mortar, and concrete was determined by the fabrication, testing, and analysis of plate specimens, each containing a precast flaw and loading hole extending through the thickness of the specimen and located at the center of the specimen.

A rigid plastic cracked strip model was developed to provide an estimate of the microcracking zone that exists in the region of a crack tip in cement paste, mortar or concrete. The experimental results were correlated with the model.

LINEAR-ELASTIC FRACTURE MECHANICS

Linear-elastic fracture mechanics is a study of the stress and displacement fields near the tip of a flaw in an ideal, homogeneous, elastic material at the onset of fracture. Its concepts are most applicable to brittle materials in which the inelastic region near the crack tip is small compared to the specimen and flaw dimensions so that the elastic stress field equations provide a good approximation.

For a material which is a homogeneous, isotropic, elastic solid, theory of elasticity provides equations which relate the elastic stresses to the stress intensity factor.(1) At a point (r, θ) in the x-y plane in the region of a crack tip for either plane stress or plane strain conditions:

$$\sigma_{xx} = \frac{K}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right]$$

$$\sigma_{yy} = \frac{K}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left[1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \qquad (1)$$

$$\tau_{xy} = \frac{K}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}$$

Similarly, the displacement fields can be denoted by the stress intensity factor.(2)

Equation 1 shows that an infinite stress exists at the crack tip in the elastic solution for the stresses. Since an infinite stress cannot exist in real materials, an inelastic deformation, such as yielding or microcracking must occur to cause a redistribution of stresses to provide stress relief. As long as the inelastic deformations are small compared to specimen and flaw dimensions, the elastic stress analysis provides a good approximation and fracture mechanics provides a means to: (a) define crack tip stress fields; (b) measure materials resistance to crack propagation; and, (c) model the crack tip zone of inelastic deformation. As a result, the concepts of fracture mechanics are useful for studying fracture and the parameters that affect it, and it makes fracture prediction possible without a complete understanding of the fracture mechanism within the inelastic region surrounding a crack tip.

FRACTURE MECHANICS APPLICATIONS TO CONCRETE MATERIALS

Several applications of linear-elastic fracture mechanics have been made to cement pastes, mortars, and concretes.(3-8) Due to the composite nature of concrete and its complex fracture process, most of the investigators treated concrete as a homogeneous, statistically isotropic material and assumed that the local stress and displacement fields in the region of a crack tip could be expressed in terms of a single parameter; i.e., the stress intensity factor, K, or the strain energy release rate, G.

Characteristic of the applications of fracture mechanics to concrete is an investigation conducted at the University of Illinois in which the effect of different concrete parameters on the fracture toughness of concrete was determined by testing 2 in. by 2 in. by 14 in. paste and mortar prisms, and 4 in. by 4 in. by 12 in. concrete prisms in flexure. The prisms contained flaws cast at the center of the tensile surface. The mix design was varied to determine the effect of various concrete parameters on the resistance of the material to propagation of an existing flaw. In the investigation it was found that the effective fracture toughness* was not significantly affected by fine aggregate content, air content, or water-cement ratio for the range of these parameters encountered in a typical mix design; however, the effective fracture toughness of concrete increase significantly as the fineness modulus of the aggregate increased and also as the amount of coarse aggregate increased. This would indicate that there have apparently been successful applications of linear-elastic fracture mechanics to concretes, but there is some evidence that the Griffith equation relating fracture stress to strain energy release may not be directly applicable to mortars and thus concretes; i.e., concretes are notch insensitive and the failure criterion is based on a limiting net section stress.

EXPERIMENTAL INVESTIGATION

The applicability of linear-elastic fracture mechanics to cement pastes, mortars, and concretes was determined by testing plate specimens, Figure 1, containing a flaw and loading hole located at the center of the specimen and extending through the thickness of the specimen. Additional series of specimens were fabricated, tested, and analyzed to verify the specimen design and experimental procedure.

Nominal dimensions of the plate specimens were 2 in. by 12 in. by W in., where W varied from 18 in. to 36 in. depending on the particular test series. The flaw and loading hole, both extending through the two

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* Effective fracture toughness is used because the fracture toughness was evaluated assuming that no crack growth occurred prior to fracture and that the concrete was homogeneous.

inch thickness of the member, were cast at the center of the plate specimen. The specimens were cast in plywood molds with the flaw formed by a strip of brass shim stock 0.002 in. thick and the loading hole formed by a section of 1.25 in. outside diameter metal pipe. The specimens were covered by plastic sheeting immediately after casting and left in that condition until the day following casting when the specimens were demolded and placed in a saturated limewater solution or an air dry environment to cure until they were to be tested.

Each plate specimen was tested by placing the specimen in the grips of the load frame, leveling the specimen, attaching the clip gages for measuring crack-opening-displacements, and applying load at a rate of 500 lb. per minute until failure occurred. A recorder produced a continuous record of applied load versus crack-opening-displacement until failure. Also, strain gages were attached to the specimen surfaces of several mortar and concrete specimens at various distances from the flaw tip in the direction of anticipated crack propagation. The strain gages were continuously monitored as the specimens were tested to failure so that the strain magnitude at various distances from the flaw tip could be obtained.

EXPERIMENTAL RESULTS

Figure 2 presents the influence of the relative flaw length,* 2a/W, on the maximum applied load for a paste series, a mortar series, and a concrete series. The results indicate that for the specimen geometry and loading used, the maximum loads which can be applied to specimens having the same nominal dimensions are inversely proportional to the total cast flaw length.

The net and gross section stresses for the paste, mortar, and concrete series of Figure 2 are presented in Figure 3. Also shown is the average net section stress, $\bar{\sigma}_n$, and a line representing the relationship between the net and gross section stresses. An additional series of specimens fabricated with the same initial flaw lengths, but with widths of 18, 24, 30, or 36 in., were tested and the results presented in Figure 4, indicate that the net section stress is not a constant for a particular specimen width, and, as the specimen width increases, the net section stress decreases. Net section stress does not, therefore, provide a valid index for concrete fracture.

The stress intensity factor, K, for the specimen shown in Figure 1 was evaluated from the following expression derived from theory of elasticity for a wedge loaded plate specimen: (1, 9)

* No significant acoustical emissions were noted prior to incipient fracture on a random sampling basis. This suggests there was no slow crack growth for these specimens and that the measured flaw length was a realistic value.

$$K = \frac{P}{B\sqrt{\pi a}} \quad \frac{1}{\left[\frac{W}{2\pi a} \qquad \frac{2\pi a}{W}\right]^{1/2}} \tag{2}$$

where P = the applied load
B = the specimen thickness
a = one-half the total flaw length
W = the specimen width.

The critical stress intensity factor is the evaluation of the stress intensity factor at the maximum applied load, which corresponds to the onset of rapid, unstable crack propagation. The critical stress intensity factors for the paste, mortar, and concrete series are presented in Figure 5 as a function of the ratio of total flaw length to specimen width. The data points shown in the figure represent the critical stress intensity factors evaluated, assuming no crack growth has occurred prior to fractures; i.e., $\omega = 0$.* The solid lines in Figure 5 present adjusted stress intensity factors, determined by evaluation of Equation 2, assuming an increase in total crack length of 2ω to account for different amounts of crack growth, or microcracking, prior to fracture.

Figures 6 and 7 present the strain values versus distance from the crack tip for various values of applied load prior to fracture obtained from the tests of mortar and concrete specimens to which strain gages had been attached. The figures show that high relative magnitudes of strain exist near the flaw tip which indicates that mortars and concretes are sensitive to flaws. Also, it is apparent that the region in which detectable strains are obtained is confined to a zone in front of the cast flaw which does not extend entirely across the width of the specimen. This would tend to negate the concept of net section stress as being an index of fracture.

The concept of linear-elastic fracture mechanics implies that the mechanism by which a crack propagates is independent of specimen geometry; therefore the critical stress intensity factor should also be independent of specimen geometry if it is a true index of fracture. The results show that the stress intensity factor varies with geometry (crack length); and, an analysis similar to that suggested by Irwin to correct for small scale yielding in metals does reduce the variation in the stress intensity factor, but does not yield a constant stress intensity factor for the micro-cracking zones assumed. Therefore, either the mechanism at failure is not independent of geometry or the stress intensity factor is not a valid index for concrete fracture.

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*ω is the length of the zone in front of the cast flaw tip over which microcracking has been assumed to occur.

MICROCRACKING MODEL

The rigid plastic cracked strip model shown in Figure 8 is a modification of the rigid plastic strip model of Rice.(10) The model consists of two elastic half planes, joined together along a strip of rigid plastic material which contains a void simulating a crack, and a zone of length, ω, which corresponds to the region of inelastic deformation; i.e., microcracking in concrete. The zone of inelastic deformation, ω, is a function of the elastic stress intensity factor, K_e, for the loading and geometry; the threshold stress, σ_{th}, for microcracking; and the stress distribution acting on the zone of inelastic deformation. The region of inelastic deformation is determined by the condition that the stresses should be bounded to eliminate the stress singularity at the crack tip.

The stress distribution acting on the zone of inelastic deformation was chosen so that with increasing microcracking of the concrete, which is determined by a limiting stress or strain condition, the model maintains a smooth transition between the linear-elastic stresses and the stress distribution along the cracked region of the model; i.e., $d\sigma_{th}/dx = 0$ at $x = 0$ and $x = \omega$. Substituting the expression for $\sigma_{th}(x)$ presented in Figure 8 into

$$K_e = -\sqrt{\frac{2}{\pi}} \int_0^{\omega} x^{-1/2} \sigma_{th}(x)\, dx \tag{3}$$

integrating and solving for ω yields

$$\omega = 0.831 \left[\frac{K_e}{\sigma_{th}}\right]^2 \tag{4}$$

which provides an estimate of the microcracking zone for cement paste, mortar, and concrete.

ANALYTICAL VERSUS EXPERIMENTAL RESULTS

If limiting strains for cracking of mortars and concretes are taken as 150 μ in./in. and 100 μ in./in., respectively, and it can be assumed that the flaw cotained in the specimens has extended an amount ω which corresponds to the distance required for the strain to be reduced to a value less than the limiting cracking strains, the strains in the direction of loading in front of the apparent flaw tip may be calculated by substituting Equation 2 into Equation 1 and then substituting the result into Hooke's Law for strains, in the y - direction,

$$\varepsilon_y = \frac{\sigma_y}{E} - \frac{\nu}{E}(\sigma_x + \sigma_z)$$

where ϵ_y = unit normal strain in y - direction.
σ_x = stress normal to y-z plane in x - direction.
σ_y = stress normal to x-z plane in y - direction.
σ_z = stress normal to x-y plane in z - direction = 0, plane stress condition.
ν = Poisson's ratio.
E = Modulus of Elasticity,

to yield

$$\epsilon_y = \frac{P\,(1-\nu)}{BE\pi\,\sqrt{2ra^*}\left[\frac{W}{2\pi a^*}\sin\frac{2\pi a^*}{W}\right]^{1/2}} \qquad (6)$$

where r = distance from flaw tip.
W = plate specimen width.
a*= Adjusted crack length to account for microcracking $a^* = a + \omega$.
P = applied load.

Figure 9 presents the strain values determined by evaluation of Equation 6. The results indicate that the strains in front of a crack tip can be determined by application of the concepts of theory of elasticity, provided an adjustment is made to the crack tip to account for the microcracking which occurs in the region of a crack tip.

Assuming that a limiting strain for microcracking exists and it is a material property for mortars and concretes, the results presented in Figure 6 and 7 indicate that as the cast flaw lengths in the mortar and concrete increase in length, the length of the region in which the limiting strain for cracking is reached decreases in size; and, the region over which the limiting strain for cracking is reached is larger for the concrete specimens than the mortar specimens. These results, indicating the relative amount of mircocracking, could account for the decrease in the stress intensity factors with increasing flaw lengths and also that the stress intensity factors are, in general, greater for concrete than for mortar. Furthermore, these results are in agreement with what the microcracking model predicts, since the model proposes a smaller microcracking zone for increasing flaw lengths. (Figure 5 shows that the stress intensity factor varies inversely with the length of the cast flaw. Microcracking zone size is directly proportional to K.) The model also predicts a microcracking zone size which is smaller for mortars than concretes. (Microcracking zone size is directly proportional to K and K, in general, is smaller for mortars than concretes.)

CONCLUSIONS

Conclusions which can be drawn from this investigation are that:

1. The concepts of linear elastic fracture mechanics are not directly applicable to cement pastes, mortars, and concretes for one

specimen geometry; therefore, the applicability of fracture mechanics to concrete materials for other specimen geometries and loadings seem questionable;

2. Other analytical techniques, such as the net section stress, do not appear applicable as a failure criterion;

3. Specimens to which strain gages were attached at different distances from the flaw tip indicate that large strains are apparent in the region of a flaw, i.e., large localized strain can occur in mortar and concrete;

4. A model for microcracking provides an indication of the microcracking zone size that occurs in concretes; however, more precise determination of the threshold stress or strain for microcracking is required for a quantitative measure of the zone size.

5. A better understanding of the cracking mechanism which occurs in the region of the crack tip in concrete under monotonic loading is needed to serve as a basis for predictions of cracking in concrete structures under both static and repeated loadings.

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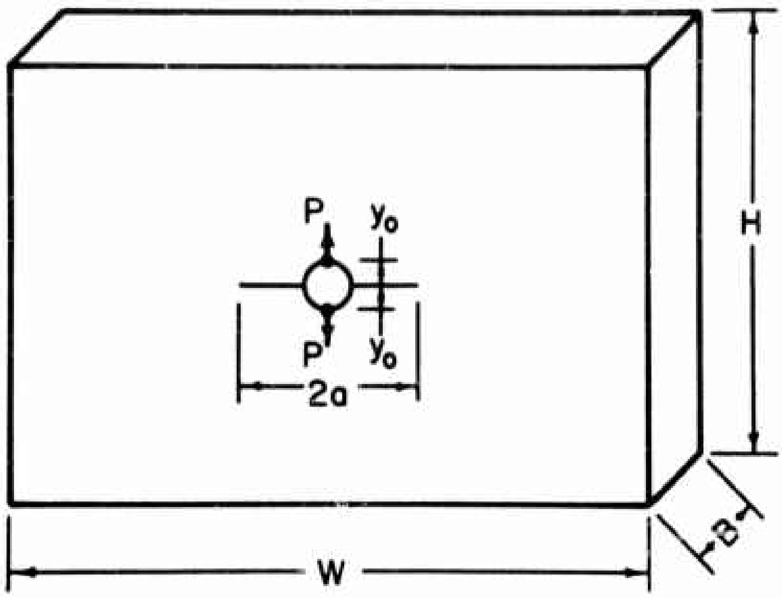

Figure 1. Plate Specimen Geometry

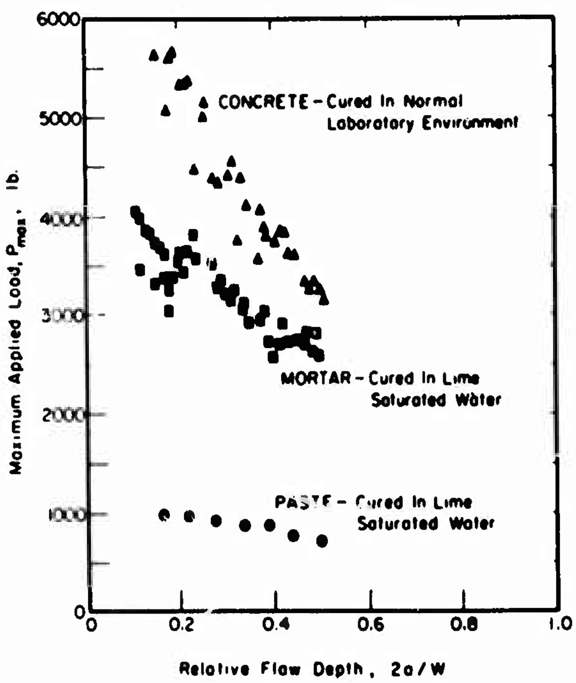

Figure 2. Influence of Relative Flaw Length on Maximum Applied Load

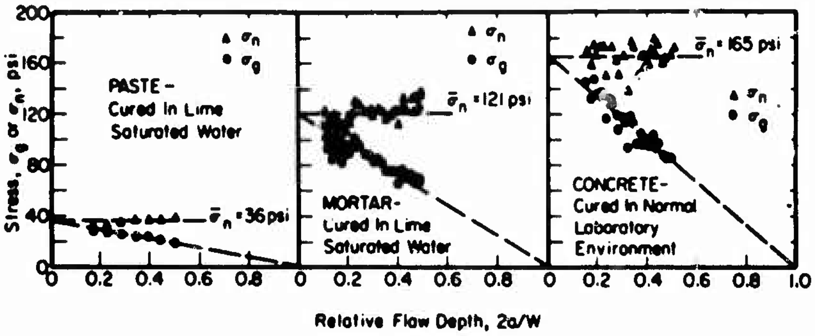

Figure 3. Influence of Relative Flaw Length on Net and Gross Section Stresses

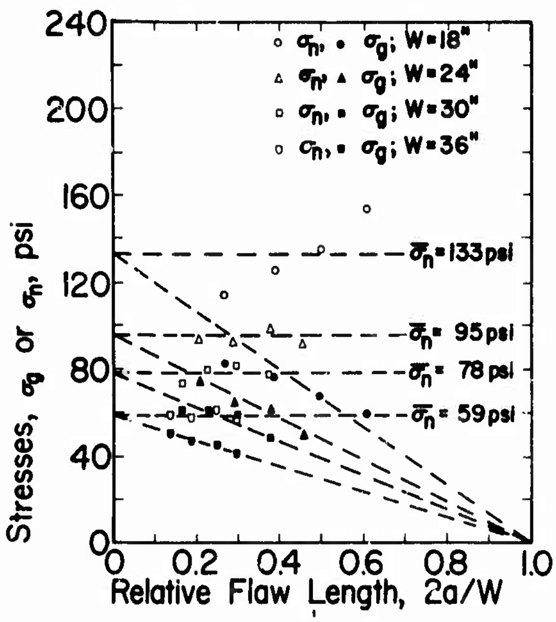

Figure 4. Influence of Relative Flaw Length on Net and Gross Section Stresses: Concrete

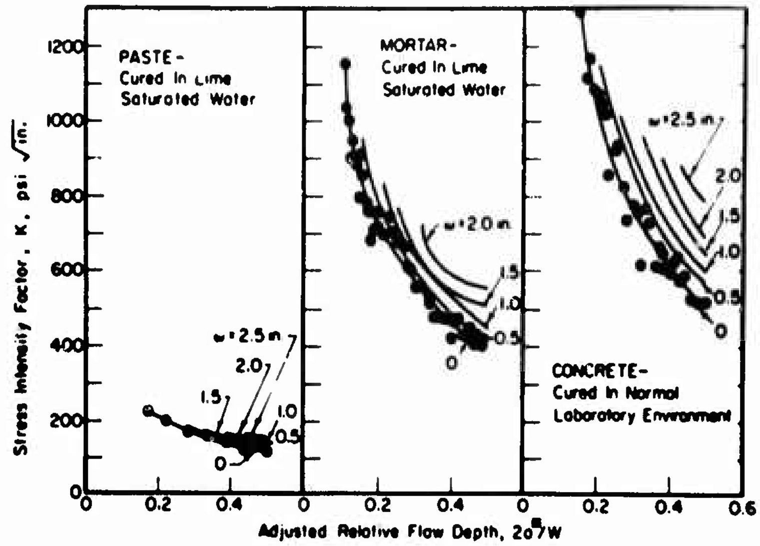

Figure 5. Stress Intensity Factor vs Relative Flaw Depth as a Function of Assumed Microcracking Zone Size

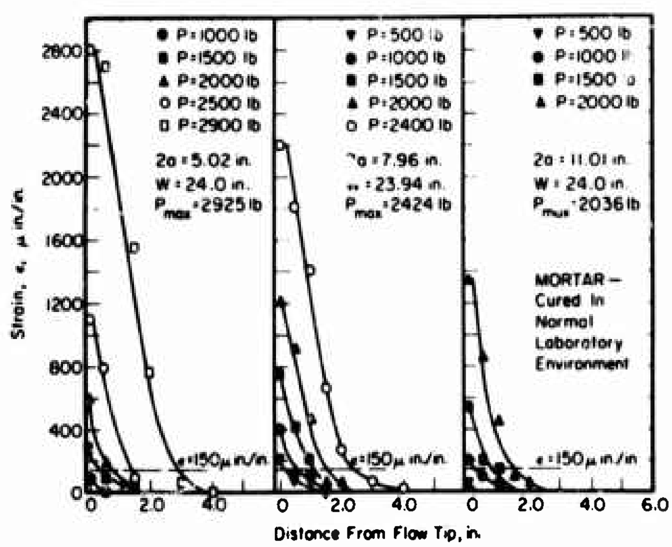

Figure 6. Strain at Various Distances from the Flaw Tip as a Function of Applied Load--Mortar

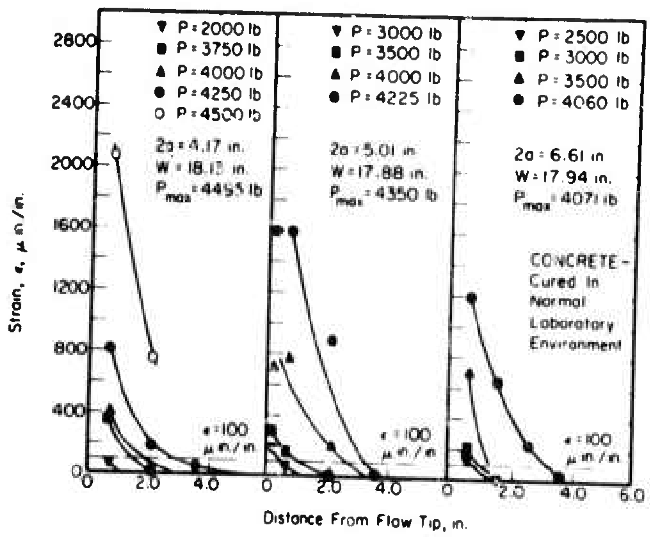

Figure 7. Strain vs Distance from Flaw Tip as a Function of Applied Load: Concrete

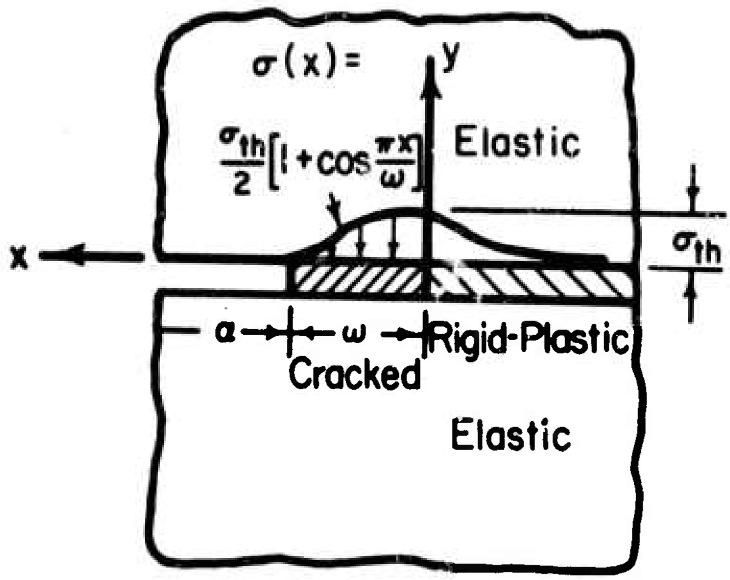

Figure 8. Microcracking Model

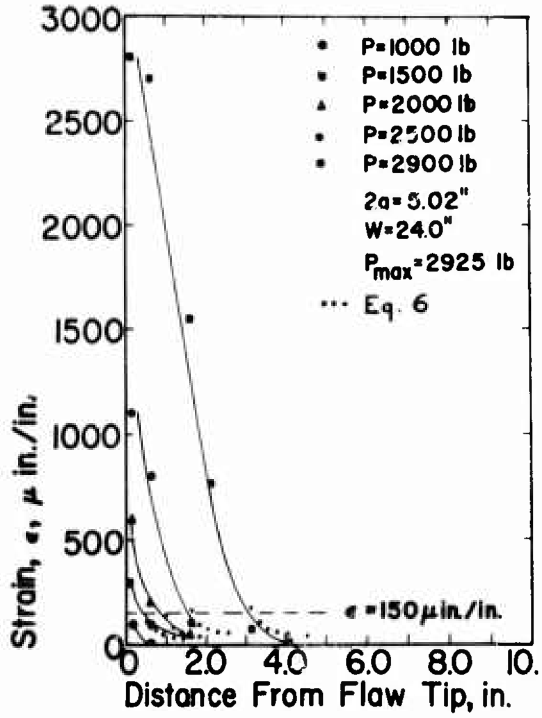

Figure 9. Strain vs Distance from Flaw Tip as a Function of Applied Load: Mortar